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Seismic Pounding of Bridge Superstructures

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Abstract

Single span bridges with deck supported on both side by elastomeric bearings are very common in seismic regions. Their main seismic vulnerabilities are related to the pounding of the deck against expansion joints. Pounding at the bridge expansion joint has been considered as one of the major causes of bridge failure from the past earthquake studies. An analytical model of Single Degree Of Freedom system is employed for pounding analysis. Laws of conservation of momentum and energy are applied for pounding response. The excitations are applied in the longitudinal direction of the bridge span. The research is aimed to study the pounding response due to gap size and to clarify the effectiveness of elastomeric pad bearing to mitigate pounding effect between adjacent decks from numerical analysis.

Keywords

Seismic pounding, Stereomechanical method, Contact element method, Elastomeric bearing, Seismic response

1. Introduction

Bridges provide passage over the obstacle without closing the way beneath. Highway bridges are the critical components of the land transportation networks as any damage to bridges can have disrupt total transportation system. However, bridges lack structural redundancy and suffer severe damage during earthquake. From the past earthquakes studies, pounding was found as the main cause of initiation of damage in the bridge.

Pounding in bridge occurs due to the relative movement and collisions of adjacent bridge structures at expansion joint. Collisions may occur between an abutment and girder, bridge deck, adjacent girders or a girder and neighboring structure due to their different phase vibrations. Most poundings of bridges last for a very short moment and are accompanied with a huge force between pounding interfaces. During that period, a mechanical energy would exchange between two pounding bodies. In almost all previous major earthquakes pounding between bridges girders have been observed. This is because the gap size of conventional bridge expansion joint is usually only a few centimeters, which is not sufficient to preclude poundings owing to large relative displacements between bridge girders caused by the effect of varying vibration properties of adjacent bridge spans, varying ground motions at bridge supports and varying soil-structure interaction (SSI).

In the past, many structural and non-structural damages in the bridge have been identified due to several strong earthquakes. In practice the expansion joint between bridge girders cannot be very large. Poundings between girders are therefore observed in almost all major earthquakes in the past. Caltrans Division of Structure Maintenance and investigations inspected over 1500 bridges and 760 bridges were found damage.Out of those 760 bridges identified as damaged, 5 bridges collapsed, and 4 bridges had major damage (no collapse) requiring demolition [1]. From the reconnaissance reports of 1995 Kobe earthquake, pounding was identified as a major cause of fracture of the bearing supports and potential contributor to the collapse of the bridge decks[2].In September 20, 1999, from the Chi Chi earthquake in Taiwan approximately 20 percentage of shaken bridges were found damaged to certain degrees out of which 20 bridges were seriously damaged[3]. In May 12, 2008, the Wenchuan earthquake occurred in Sichauan Province, China. Nearly 1600 bridges along the main roads were damaged extensively. Based on the investigation of Baifua Bridge, the failure in bridge was due to bridge moved in the transverse direction, lateral beams detached from the column at the joints, dislodging of superstructure due to excessive lateral displacement and uplift [4]. In April 2016, a series of earthquake occurred in Kumamoto, Japan. Among the 3,000 bridges in Kumamoto Prefecture, about 40 bridges were severely affected by earthquake. During this earthquake, girder fell off from its rubber bearing in Ookirihata Bridge as the rubber bearing underwent shear destruction and the girder experienced relative displacement of about 70 cm in transverse direction[5].

The result from impact force response spectrum using the single-degree-of-freedom structural models showed that tuning the dynamic parameters of both structures, so that they might vibrate in-phase, or providing sufficient separation between them will minimize the negative effects of pounding or even prevents contact at all[6]. It was found that the maximum relative displacement between two bridge segments that are connected at joints was amplified due to the pounding effect [7] . Past research has shown that the pounding effects can be reduced by providing adequate gap or by providing damper or by designing the structure to withstand pounding force. Most of the past researches have been focused on providing the restrainers, bumper , dampers [8], modular expansion joints [9] on mitigation of pounding. But the bearing provided in the bridge and its contribution on pounding mitigation has rarely been studied. Even though the primary purpose of bearing is to transmit load from superstructure to substructure, they also accommodate the relative displacement between superstructure and substructure. The reconnaissance report from January 26, 2001 Gujarat earthquake however have shown that Elastomeric bearings are not suitable for use in high seismic regions [10].

An analytical model of SDOF system has been employed for pounding analysis. The research is aimed to study the effect of gap size on pounding number and to clarify the effectiveness of elastomeric pad bearing designed considering IRC 83 part II [11] in eliminating the pounding effect between adjacent decks from numerical analysis. However the ground motion is limited to longitudinal motion and the bridge skewness, multisupport excitation and soil structure interaction is not considered.

2. Analytical model and basic equations

The interaction between the slab and the abutment of a single span bridge plays as important role in seismic response. Figure (1) shows the analytical bridge model used in the study. The bridge frame is idealized as single degree of freedom yielding element with mass m resting on rigidly placed bearing with horizontal stiffness k and damping coefficient c.

The equation of motion subjected to ground acceleration can be represented as

$$mx'' + cx' + kx + F_{\mathrm{p}} = -mu_{\mathrm{g}}'' \qquad (1)$$

Where,

m = Mass of frame

c = Damping coefficient of frame

k = Horizontal stiffness of frame

F_p= Force due to pounding

u_g”= Longitudinal ground acceleration

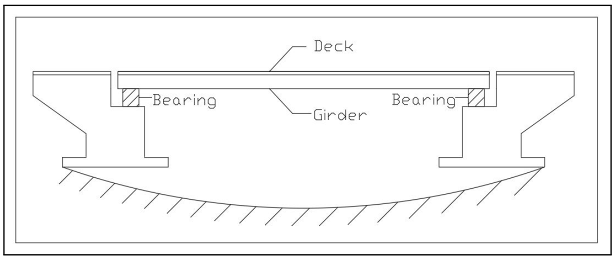

Figure 1: Typical single span bridge

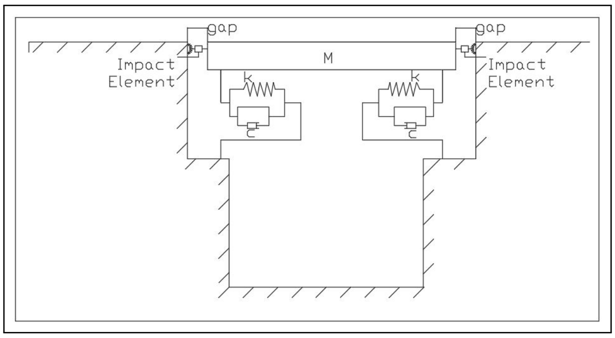

Figure 2: Analytical bridge model used in study

Dividing by m on both sides of equation (1)

$$x'' + 2\zeta(x)' + w^2x + F_{\mathrm{p}}/m = -u_{\mathrm{g}}'' \qquad (2)$$

The solution for equation (1) can be obtained in the time domain using a numerical time stepping algorithm. Among the several methods available for solving the equation, Runge Kutta method is adopted as this method is easy to implement, requires no special starting procedure and is numerically stable.

Pounding occurs when the displacement is greater than provided gap (i.e. x > gap).

In case of stereomechanical model,x is calculated for each time step assuming pounding force to be zero. However, the velocities of colliding masses after impact are adjusted as follows

$$v_1{}' = v_1 - (1+e)\frac{(m_2(v_1 - v_2))}{(m_1 + m_2)} \quad (3)$$

$$v_2{}' = v_2 + (1+e)\frac{(m_1(v_1 - v_2))}{(m_1 + m_2)} \quad (4)$$

where, v_1, v_2 are the velocities before impact and v_1' and v_2' are the velocities after impact.

3. Selection of Bridge Model

For the study of the effect of gap size on pounding response, a typical small span T-beam Bridge of 20m span is selected with following properties.

Effective Span = 20m
Carriageway = 7.5 m
Kerb width = 1.75m
Slab Thickness = 0.23 m
Wearing Coat thickness = 0.05 m
CSA of L-girder = 0.4 x 2
CSA of X-girder = 0.3 x 1.5
Total Load = 2583 kN
No. of bearing = 6
Load per bearing = 430.5 kN
Impact Area = 10.184 m^2

Figure (3) shows the cross-section of bridge taken into consideration.

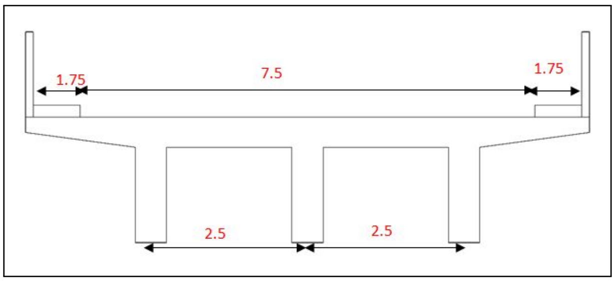

Figure 3: Cross Section of the Bridge

The cross sectional area and thickness of bearing provided is 11.6x10^4 mm^2 and 50 mm respectively.

For the response of elastomeric bearing on a single superstructure of a bridge, the load acting upon the elastomeric bearing are calculated based upon the permissible normal load as given by IS 83 part II [11].

4. Ground Motion Selection and Input

The target spectrum was taken from IS 1893 (Part I): 2002 [12]. Then five real and one artificial seismic excitations were synthesized using SeismoArtif program for Type I (Rock or Hard Soil), Type II (Medium Soil) and Type III (Soft Soil). The response spectrums of the three ground motions, as well as the mean and target spectrums, are shown in Figure (4), (5) and (6). It can be observed from the figure that the spectrum of the ground motions matched well with the target spectrum. The vertical seismic excitation was neglected in this study. The average value of the calculated analytical results from the six seismic excitations was used in this study for discussion.

Earthquakes Considered

1. Chi-Chi Earthquake
2. Friuli Earthquake
3. Hollister Earthquake
4. Imperial Valley Earthquake
5. Trinidad Earthquake
6. Artificial Earthquake

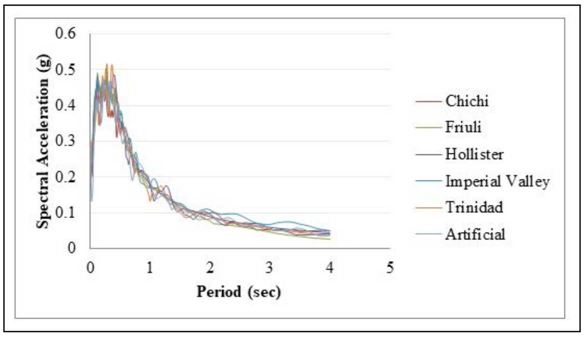

Figure 4: Target Spectrum Vs. Spectrum of selected ground motion (Type I)

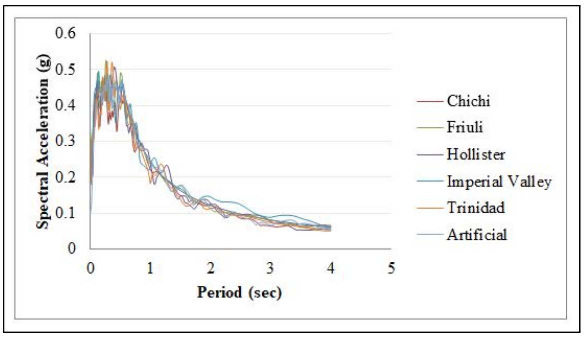

Figure 5: Target Spectrum Vs. Spectrum of selected ground motion (Type II)

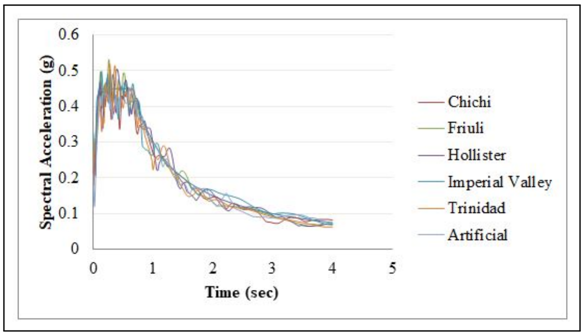

Figure 6: Target Spectrum Vs. Spectrum of selected ground motion (Type III)

5. Influence of elastomeric bearing in pounding

The areas of different elastomeric bearing as provided in IRC 83- Part II [11] were used for the study. Maximum permissible displacement of the bearings for maximum and minimum normal load per bearing as provided in code after consideration of the displacement due to creep, shrinkage and temperature for different size index number is plotted.

Shear strain due to creep, shrinkage and temperature

$$= \frac{\text{Longitudinal Strain} \times \text{Effective Span}}{\text{No.of bearing} \times \text{Bearing thickness}}$$

For common RCC Bridge decks,
Longitudinal Strain = 5×10^{-4}
Available shear strain for earthquake force = Total shear strain – Shear strain due to creep, shrinkage and temperature

It is observed from figure (7) that for both maximum and minimum normal load per bearing, the permissible displacement increases with the size index number. However, the permissible displacement for maximum normal load per bearing (for both maximum and minimum thickness of bearing) is greater than that of minimum normal load per bearing in each size index number. Also the permissible displacement for greater thickness of bearing is greater than that of smaller thickness of bearing. Similar is the case for shear strain of bearing as seen in figure (8). As the displacement is obtained by multiplying the strain with corresponding bearing thickness, and since the gap between minimum and maximum thickness increases with size index number, the graph in figure (7) is diverging with size index number while the graph in figure (8) is seen converging.

Comparing the permissible shear strain of the bearing with the maximum shear strain due to earthquake, the bearing effectiveness is determined.

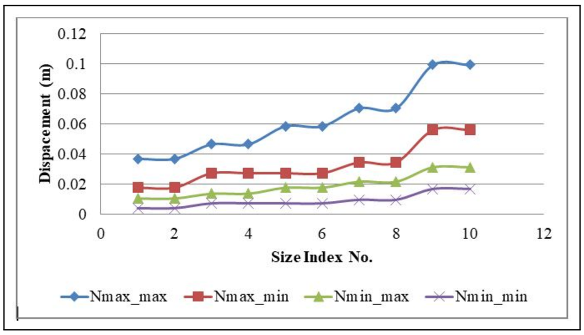

Figure 7: Permissible displacement of bearing Vs Size index No.

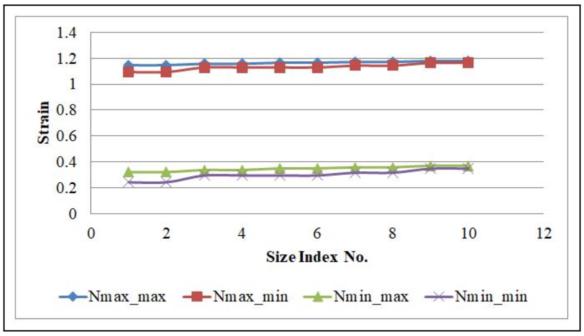

Figure 8: Permissible strain of bearing Vs Size index No.

6. Bearing Designed From Maximum and Minimum Normal Load per Bearing

For the design considering maximum normal load per bearing and maximum thickness from each size index number, size index no. 9 and 10 was found to resist the earthquake motion without failure of bearing for all earthquake in Type I soil and some earthquake in Type II. Out of the six earthquakes considered, bearing of size index no. 7 and 8 did not fail for four earthquakes (Type I) and size index no 5,6 did not fail for 2 earthquakes (Type I).

Size index no. 9 and 10 was found to resist the earthquake motion without failure of bearing for one earthquake in Type I soil for design considering maximum normal load per bearing and minimum thickness from each size index number. Bearing of other size index failed in shear for all earthquake and soil types considered.

All the bearings failed in shear for bridges designed considering minimum normal load per bearing and both maximum and minimum thickness from each size index number.

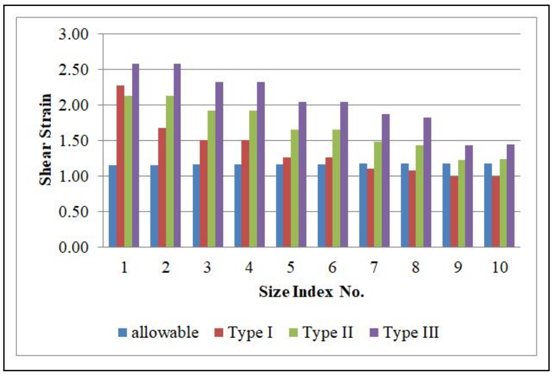

Figure 9: Variation of Shear Strain with size index no. for Maximum normal load per bearing (Maximum thickness from each size index)

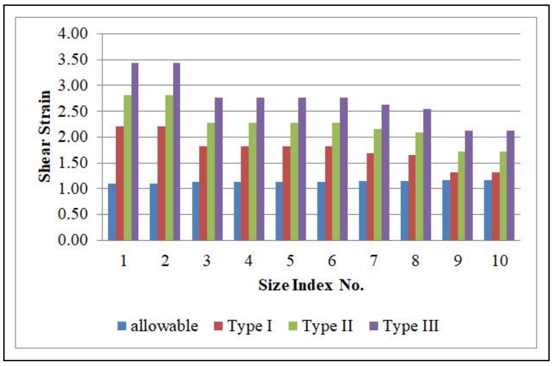

Figure 10: Variation of Shear Strain with size index no. for Maximum normal load per bearing (Minimum thickness from each size index)

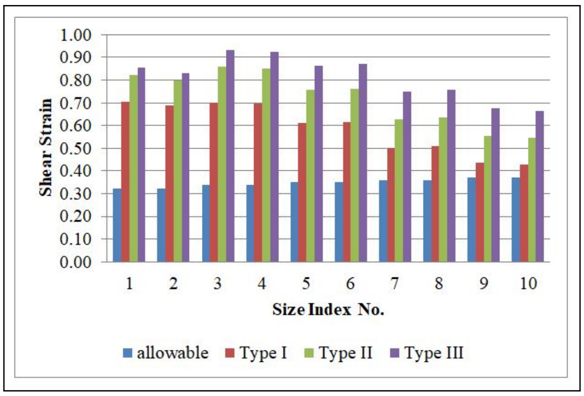

Figure 11: Variation of Shear Strain with size index no. for Minimum normal load per bearing (Maximum thickness from each size index)

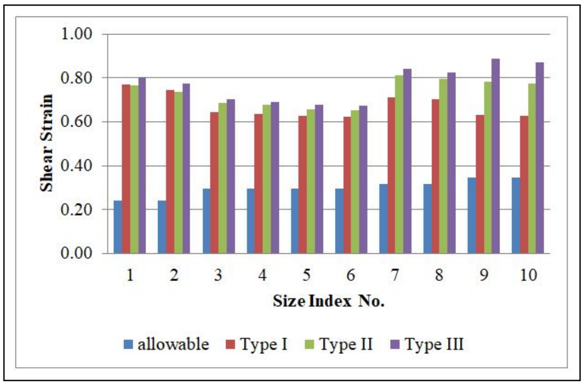

Figure 12: Variation of Shear Strain with size index no. for Minimum normal load per bearing (Maximum thickness from each size index)

Comparing the shear strain of the structure in different type of soil from synthesized motions, it is observed that shear strain depends upon the type of ground motion. However, from 240 compared records, about 95% results showed that shear strain is of order Type III > Type II > Type I.

A representative plot showing the variation in shear strain with size index number considering the case of Chi-Chi earthquake is shown in figures 9, 10, 11 and 12.

7. Bearing Designed for Same Load per bearing

IS code [11] has set the criteria for the design of bearing from different size index no. putting the upper bound and lower bound in the normal load per bearing.

A normal load per bearing of 920 kN is taken and is designed from size index no. 5, 6, 7, 8, 9 and 10 considering maximum thickness from each size index no for the two earthquakes which did not fail in shear. It is seen from figure 13 that even with the increase in the size index number, the bearing fails in shear. It is due to the reason that when same normal load per bearing is taken, it is similar to designing the bearing with lower size index no. with maximum load per bearing and designing the bearing with higher size index no. with minimum load per bearing. As obtained from the earlier section as all the section fails when designed with minimum load per bearing, bearing from lower size index no. doesn't fail whereas bearing from higher size index no. fails in shear.

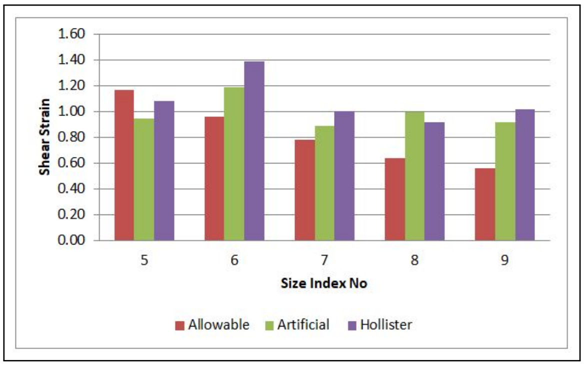

Figure 13: Variation of Shear Strain with size index no. (Type I)

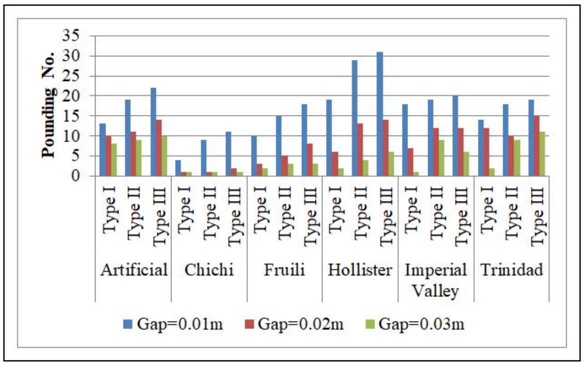

Figure 16: Variation of pounding number with gap size for different Ground type (Right end Restriction)

8. Effect of Gap Size on Pounding Number

If pounding is to be avoided, the gap provided should be the absolute maximum displacements at both ends due to their responses to the earthquake motion considered. To study the effect of gap size on pounding, the gap size is varied from 1cm to 3 cm at an interval of 1 cm.

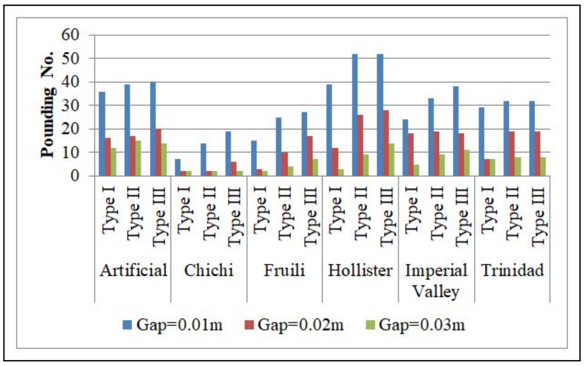

Figure 14: Variation of pounding number with gap size for different Ground type (Both end Restriction)

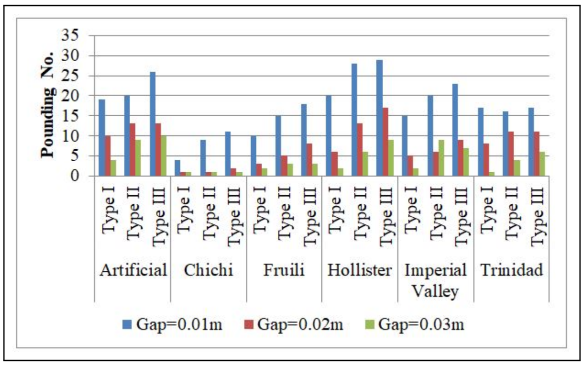

Figure 15: Variation of pounding number with gap size for different Ground type (Left end Restriction)

Figure (14), (15) and (16) shows the variation in pounding number with gap size for different restriction condition. It is seen that the pounding number in type II is greater than type I and pounding number in type III is greater than I and II both. Within the same restriction condition, the pounding number is found decreasing with the increase in gap size.

During an earthquake, the displacement of the structure is such that the number of larger displacement is always less than that of smaller displacements. At pounding, the response of the structure changes significantly. Due to this change, both side pounding is affected more than one sided pounding as in one sided pounding the structure is allowed to displace freely on one side. It is due to this; pounding in larger gap size is sometimes obtained greater than in small gap size. But overall, due to the less number of larger displacement, the pounding number decreases with gap size.

9. Conclusions

This paper presents the analytical model of SDOF system for pounding analysis. By utilizing this model, effectiveness of elastomeric bearing and effect of gap on pounding number has been has been obtained from numerical analysis. The conclusions of this paper are as follows :

1. Overall the displacement of the elastomeric bearing designed considering IS code alone do not meet the displacement demand of the earthquake. For the bearing to remain safe in shear, ballast wall is to be designed to sufficiently resist the pounding force.
2. The service life of the elastomeric bearing is normally 15 to 20 years. As the service life of

the bearing is very much less than the recurrence of the large earthquake, the present practice suits the design of bearing as the bearing can be sacrificed for the large earthquake. However, for the bearing to be designed with increase in service life and accommodate the large earthquake, it should be provided with greater thickness and designed from lower size index no possible.

3. Shear strain and pounding number are affected by the type of soil. It is found in the order of

$$\text{Hard Soil} < \text{Medium Soil} < \text{Soft Soil}$$

4. The numbers of occurrence of pounding decreases with increase in gap size.

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